INVESTIGATION OF A LOW DENSITY PLASMA UTILIZING LASER LIGHT SCATTERING

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THESIS

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ABSTRACT

Measurement of plasma density and temperature was attempted using the technique of scattering laser light from the plasma and comparing the magnitudes of the scattered and input intensities. Although no significant results were obtained, a scattered signal was apparently obtained using a giant pulse laser. Both PIN photodiodes and photomultiplier tubes were used as detectors, and comparison showed the photomultipliers were more suitable. The most important results were modification of the laser to operate with a Pockels cell in a "Q"-switched mode, improvement of the optical alignment system, and use of a light trap to eliminate internal reflected signals.

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I. INTRODUCTION

The beam from a high power laser provides an excellent mechanism for determining the density and temperature of a plasma. In order to obtain these quantities the laser is fired at the plasma and the intensity of the scattered laser signal is measured. If the laser pulse shape and intensity are also known, the plasma parameters may be calculated from applicable equations which will be discussed in section two. It is appropriate to mention that although the method is relatively simple, several factors make these measurements extremely difficult. Chief among the difficulties encountered was the fact that the ratio of scattered to incoming light intensity is of the order of 10^{-15}. This resulted in an extremely low scattered light signal. Another obstacle was the radiation emitted from the plasma. Almost all of the gases used had at least one line within a few angstroms of the ruby wavelength. Elimination of the effects of the plasma radiation was accomplished but the low signal required that the oscilloscope be operated at a high gain and with this electronics problems caused by pickup of stray signals ensued.

At the Naval Postgraduate School, efforts have been directed toward detection of a laser signal scattered at an angle of 90° from the plasma. Initial research was started in 1969 by Lieutenant A.E. Pease [Ref. 1] and was continued

in 1970 by Captain T.F. Alger [Ref. 2]. The research done during this experiment was conducted with a detection system similar to that used by Captain Alger. Lieutenant Pease employed a three-meter spectrograph and photomultiplier tubes with the intent of eliminating all unwanted signals by tuning exactly on the ruby wavelength. Although this approach insured that a detected signal would be from the laser, the required alignment seriously limited its use.

Scattered laser light has been detected in several experiments. Fünfer, Kronast and Kunze investigated a theta-pinch plasma and found that an electron density of 10^{17} cm^{-3} gave a ratio of scattered to input intensity of 10^{-11} [Ref. 3]. A forward scattering technique was used. It is estimated that electron density in the plasma chamber at the Naval Postgraduate School is about 10^{-13} cm^{-3} so that, as previously stated, the power ratio is 10^{-15}.

Detection of the scattered signal can be accomplished by placing the detector at 90°, forward or backward from the plasma. According to Kunze [Ref. 4], the 90° method is more accurate when stray light is present and it also permits measurements to be taken on a specific volume element in the plasma so that local plasma parameters can be obtained. Forward scattering experiments are quite sensitive to changes in the scattering angle and reduction of stray light from the plasma is difficult to achieve. Results from back scattering are not as critically dependent on the scattering

angle as are those from forward scattering, but with both methods the information obtained is not characteristic of a specific point in the plasma. The plasma chamber [Figure 1] consists of a vacuum system containing a series of observation ports located along the sides and top. The position of ports made the use of the 90° method feasible, and it was used during the entire experiment.

II. THEORY

In order to calculate the amount of light which should be scattered, the cross section must be known. The following derivation of the Thomson cross section is given, since intensity calculations are based on its use. A more detailed description appears in Ref. 5.

An electron initially at rest is given an acceleration, $\dot{\bar{V}} = \frac{e}{m}\bar{E}_i$, when subjected to the effects of a plane, monochromatic wave with electric vector $\bar{E}_i = E_0 e^{j\omega_i t - j\bar{k}_i \cdot \bar{\rho}}$

E_0 = maximum amplitude of oscillation

$\bar{k}_i$ = propagation vector

ω_i = angular frequency

The scattered signal, $\bar{E}_s$, is given by

$$\bar{E}_s = \frac{e}{4\pi\varepsilon_0 c^2 R}\,[\hat{q} \times (\hat{q} \times \dot{\bar{V}})]t' \qquad (1)$$

where $t' = t - \frac{r}{c} + \frac{\hat{q}\cdot\bar{\rho}}{c}$

and $\hat{q}$ is a unit vector in the direction of scattered radiation. The scattered radiation will have the same frequency and wavelength as the incident radiation.

Power scattered per unit solid angle, $d\Omega$, is

$$\frac{dW}{dtd\Omega} = \left|\bar{S}_i\right| r_0^2 \left|\hat{q} \times \left(\hat{q} \times \frac{\bar{E}_i}{|\bar{E}_i|}\right)\right|^2 \qquad (2)$$

$|\bar{S}_i|$ = magnitude of Poynting flux of incident wave

r_0^2 = square of classical electron radius

Referring to Figure a, the term $\left|\hat{q} \times \left(\hat{q} \times \frac{\bar{E}_i}{|\bar{E}_i|}\right)\right|^2$ reduces to $1\text{-}\mathrm{SIN}^2\theta_s[\mathrm{COS}^2(\phi_0 - \phi)]$, where θ_s is the angle of scattering. Equation (2) may be represented by

$\frac{dW}{dtd\Omega} = \left|S_i\right|\sigma_T(\theta_s)$ where $\sigma_T(\theta_s)$ is the Thomson differential cross section and is $\sigma_T = r_0^2\ (1 - \mathrm{SIN}^2\theta\mathrm{COS}^2\ (\phi_0 - \phi)\ )$.

The total cross section is obtained by integration of $d\Omega$ and is $\sigma_T = \frac{8\pi}{3} r_0^2$ (6.65×10^{-25} cm^2). It is noted that the Thomson cross section is independent of the frequency of the incident radiation. The mean free path, $\frac{1}{n\sigma_e}$, is so great

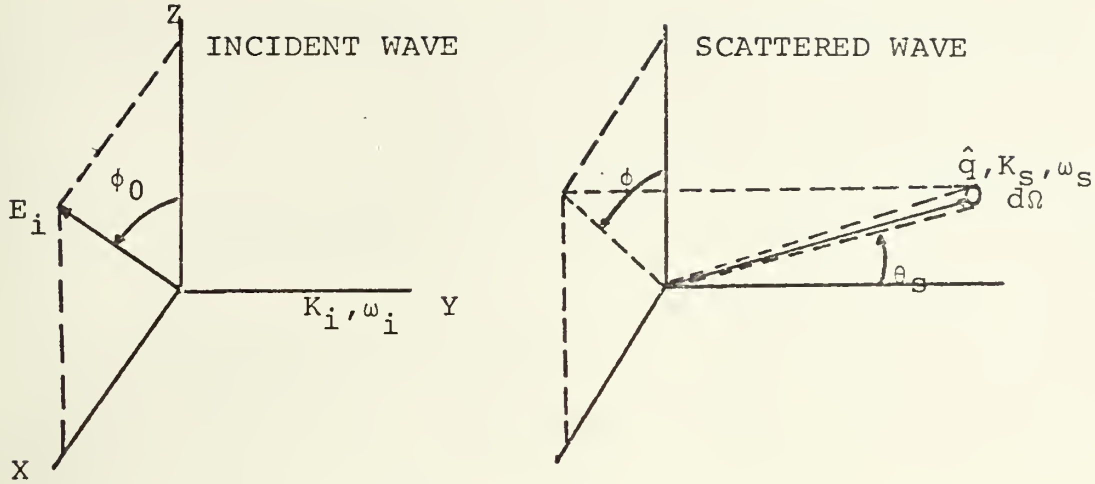


Figure a. (Ref. 5)

that the probability of multiple scatterings is practically non-existent.

The cross section previously calculated does not include the effects of electron motion, which will have an effect on the frequency of the scattered radiation. The Doppler shift, $\Delta\omega$, is equal to the scalar product $\bar{K}\cdot\bar{V}$, where $\bar{V}$ is the velocity of the electron and $\bar{K}$ is the vector difference between $\bar{K}_0$, the original direction, and $\bar{K}_s$, the scattered direction. Details of the calculation are given in Ref. 4, and, with the approximations used, only the frequency of the scattered radiation is changed. The Thomson cross section remains the same. Relativistic effects are negligible under the conditions used in the Naval Postgraduate School plasma chamber.

The ratio of scattered to incident intensity is given by the formula

$$\frac{W\lambda}{L\lambda} = \sigma_T n_e S(k)\,dZ\,d\Omega \tag{3}$$

σ_T = Thomson cross section

$S_{(k)}$ = form factor (set equal to one)

n_e = electron density

and is about 10^{-15} for the Postgraduate School plasma chamber.

In addition to the ratio of scattered to input intensity, the self-radiation of the plasma must also be considered since it also will have an effect on the detected signal. Calculations in Ref. 2 show that the ratio of scattered to plasma light may be represented by

$$\frac{W\lambda}{P\lambda} \propto \frac{\lambda}{n_e} L_\lambda \tag{4}$$

W_λ = scattered intensity

P_λ = plasma intensity

L_λ = input intensity

n_e = electron density

From this relationship it is apparent that as density decreases the ratio becomes more favorable. However, it is also noted that as density is decreased, the ratio of scattered to input power is also decreased. Since it was nec-

essary to have the density as large as possible, a special method was used to cancel plasma noise.

A parameter, α, defined as $\frac{1}{|K|\lambda_d}$, (λ_d = de Bye length) is necessary to determine the correlation of electron motion. With $\alpha << 1$, the scattering is completely uncorrelated. With $\alpha >> 1$, electron motion is determined exclusively by interaction between particles and is correlated. Thomson scattering occurs with $\alpha << 1$ and in experiments conducted at the plasma facility, the $\alpha << 1$ criteria is satisfied.

With this condition existing, a Gaussian profile for the spectrum of the scattered radiation is obtained. This spectrum is

$$S_T(\bar{k}\omega)\,d\omega = n_e \sqrt{\frac{m}{2\pi|K|^2\kappa T_e}} \quad \exp\left(\frac{m\omega^2}{2|K|^2\kappa T_e}\right) d\omega \qquad (5)$$

T_e = electron temperature

κ = Boltzmann constant

and is arrived at by using the Doppler equation $\omega = \bar{K}\cdot\bar{V}$. Further, we may represent the differential cross section as $\frac{d^2\sigma}{d\omega d\Omega} = \sigma_T S_T(\bar{k},\omega)$. The objective is to determine the electron temperature. The temperature is easily determined with relative measurements since the half-width of the Gaussian profile is dependent only on electron temperature.

$$\Delta\,\omega_{1/2} = 4\omega_0 \;\mathrm{SIN}\,\theta/2 \sqrt{\frac{2\kappa T_e \ln 2}{mc^2}} \qquad (6)$$

However, exact measurements of intensity must be made to determine density. It is calculated from Equation 5.

III. EXPERIMENTAL APPARATUS AND ALIGNMENT

A. APPARATUS

Figure 2 shows the equipment used to conduct the experiment. The apparatus consisted of a helium-neon continuous wave gas laser, a Pockels cell with Brewster stack polarizers, pulsed laser, focusing lenses, periscope, monochromator, calcite slab, beam splitter, photomultiplier tubes and a PIN photodiode used as an external trigger source. The power supplies for the pulsed laser and Pockels cell are visible in the foreground of the photograph at the left.

The gas laser was indispensable as a tool for aligning the entire system. Its ability to produce an intense collimated beam provided excellent simulation of the beam from the pulsed ruby laser and also was used for alignment of the Pockels cell and rear reflector.

The Lasermetrics model EOM-817 Pockels cell was used to "Q" switch the laser so that a high intensity, short pulse was obtained in the range of 50 to 100 megawatts. The laser and Pockels cell were aligned so that the laser pulse emitted was horizontally polarized. Details of this scheme are found in the alignment procedures.

The Pockels cell functioned by blocking the passage of light from the rod to the rear reflector. This was accomplished by applying a predetermined voltage to the terminals

of the cell. When this voltage was removed, the wave propagating through the crystal in the cell underwent a shift in polarization so that light of the desired frequency, in this case ruby light, was transmitted. A Brewster stack was placed between the Pockels cell and ruby rod and was positioned so that it transmitted light in a horizontally polarized direction only. The ruby rod was also placed so that the "C" plane, a preferred direction within the rod, was horizontal. In this position, the light emitted from the ruby rod was horizontally polarized in both conventional and "Q"-switched modes of operation. With the rod and Pockels cell in the proper position, and voltage applied to the Pockels cell, no lasing can occur because the Pockels cell is vertically polarized while the other components are horizontally polarized. After a preset time, the voltage is removed by the pulse generator and this has the effect of shifting its plane of polarization 90 degrees so that all components are aligned and lasing occurs. The voltage applied to the Pockels cell was determined from a graph in Ref. 6 to be 4000 volts, and was experimentally confirmed. The time delay was determined experimentally to be optimum when the voltage was removed 700 microseconds after the flashlamps fired. To achieve this delay, the pulse burst generator was triggered from the same signal which triggered the flashlamps. The generator contains a built-in delay circuit and the amount of delay is selected on the control

panel. The pulse generator is capable of producing from one to 30 pulses of variable duration and separation in a single burst, and its output can be conveniently monitored through a sampling output terminal. The laser used in the investigation produced best results when a single pulse was applied from the burst generator. The laser pulse length was approximately 100 nanoseconds when a single burst was applied using a 700 microsecond delay with 4000 volts across the Pockels cell. This is relatively long and in fact Ref. 7 states that the pulse length should be 20 to 40 nanoseconds for the Optics Technology 130 laser which was used. That figure, however, is applicable when the "Q" switching is accomplished by a Kerr cell or bleachable dye which is placed between the ruby rod and front etalon in the laser housing. In order to accommodate the Pockels cell and Brewster stack, the rear reflector was removed and placed as shown in Figure 3. This displacement more than doubled the length of the lasing cavity and was responsible for the long pulse length. References 6 and 8 provide more detailed information about the capabilities and operation of the Pockels cell and pulse burst generator.

The Optics Technology laser original configuration had a permanently mounted, totally reflecting rear prism instead of the adjustable, dielectric-coated mirror that is now used. A hole was drilled in the rear panel of the housing so that the gas laser could be positioned behind the pulsed laser. Then the beam from the gas laser could be adjusted

to pass through the rear mirror, ruby rod, and front etalon in a manner which exactly simulated the pulsed laser beam.

The pulsed laser, when operated in a conventional mode, produced a pulse of about 500 microseconds length. Energy output in this mode was approximately five joules, but peak power was only 20,000 watts. The "Q"-switched mode did not release as much energy, but power was estimated to be between 10 and 50 megawatts. Since the ability to detect the pulse was directly proportional to power output, the "Q"-switched mode greatly increased the probability for detection of the scattered signal.

The focusing lens placed in front of the laser had a focal length equal to the distance between the lens and the plasma column. Because of this, the laser pulse was focused to an extremely fine point at the plasma. This was verified by firing the laser at an aluminum rod which was placed in the chamber by extending it through the hollow cathode. Examination of the rod after firing revealed several scored areas of small size which indicated that the laser beam was indeed focused to almost a pinpoint.

Opposite the entrance port for the laser beam is another port used for observation of the plasma. After firing several times with the plasma chamber empty and still detecting signals, it was apparent that internal reflections were responsible, and it was suspected that they emanated from the glass covering the observation port. The possibility that the laser beam was striking the cathode was also

acknowledged, but aiming the beam sufficiently far to the left to insure that the cathode was not hit produced no noticeable decrease in the reflected signal. A light trap, as pictured in Figures 1 and 3, finally provided the solution. The light trap was inserted with the use of a rubber stopper and metal rod, which allowed easy placement. The best position was found to be about one inch from the end of the port as indicated in the diagram.

The light trap is designed so that the two glass plates make an angle of 60° with the front edge. The glass transmits about 10^{-5} of the incoming light and that portion which is reflected is almost completely absorbed by the walls. With the glass placed at 60°, approximately the Brewster angle, reflection of the horizontally polarized ray is minimum. The design used was a simplified modification of a light dump described in Ref. 4. The entire cylinder was coated with optical black paint and the glass used was an F12 filter normally used in welder's goggles. Removal of the light trap showed a slight amount of coating on the surface exposed to the plasma. This coating, which was slightly reflective, was found on both the painted portion and the glass and appeared to be of an oily nature formed when the plasma was formed. It evidently did not cause any significant reflections, however, since measurements were made down to 200 microvolts with plasma off, and no reflected signal was discernible.

The periscope used was designed so that it would transmit a beam of parallel light scattered from the plasma, or rod simulating the plasma, to the focusing lens mounted in front of the monochromator. This was accomplished by determining the height required for transmission, and the tube holding the periscope was constructed so that the beam would be at the proper height. A lens was mounted inside the tube of the periscope so that it could be positioned at exactly one focal length above the plasma column. The internal mount for the lens was such that it traveled inside the tube without changing the height of the periscope prism, and thus the alignment with the monochromator was preserved. Focusing the alignment beam on the ceiling placed the lens at the proper distance.

The port over which the periscope was mounted was originally about four inches above the plasma chamber. After several runs with the plasma on, it was discovered that the crystal used in the aperture was becoming coated. This coating greatly reduced the amount of light transmitted to the periscope and finally made the crystal so opaque that the alignment beam was invisible. An extension was made for the aperture so that the crystal was moved about one foot above the chamber, and this eliminated all coating of the crystal.

The lens used to focus the parallel light from the periscope onto the monochromator slit had a focal length equal to the distance between the slit and the rear mirror of the monochromator. This distance was used so that the

image size on the mirror would provide maximum intensity at the exit slit. The monochromator was calibrated using several light sources of known wavelength. The setting for ruby was obtained by subtracting 85 from the setting giving the maximum signal for the gas laser. The approximate settings were 680 for the continuous beam and 595 for the ruby. Although the actual settings varied from day to day, the difference of 85 remained constant. On several occasions, the ruby setting was confirmed by scattering off an aluminum rod.

The purpose of sending the light through the monochromator was to reduce the background radiation as much as possible. When using argon or nitrogen for the plasma, there are several spectral lines within a few angstroms of ruby,which could not be eliminated. They were reduced somewhat by closing the slit, but the monochromator did not have the resolving power necessary to distinguish between these lines and the ruby. Because of the necessity of having the highest possible intensity of scattered light, and the least possible interference from the plasma, a method used by Captain Alger was employed.

This method, described in Ref. 2, takes advantage of the fact that light from the laser is horizontally polarized, while light from the plasma is unpolarized. When the plasma light passed through the calcite slab, mounted just outside the monochromator exit slit, it was divided into two components; one was horizontally polarized, and the other was

vertically polarized. The separation of the rays is determined by the thickness of the calcite, and is such that they are focused on two mirrors at the rear of the beam splitter. The ray striking one mirror contained the horizontally polarized component of plasma radiation, and the ruby light, while the ray striking the other mirror contained only the vertical component of plasma radiation. These rays were reflected onto photo detectors, and the signals were fed to a differential amplifier where the horizontal and vertical components would cancel, and only the scattered laser signal would remain. However, it was observed that the vertically polarized ray was less intense than the horizontal component, and this made compensation between the detectors necessary. This difference was probably caused by absorption or reflection of the vertical component within the crystal.

The first detectors mounted on the beam splitter were HP 5082-4205 PIN photodiodes, which have good response in the ruby wavelength region [Ref. 9]. An optical wedge was installed on one of the mounts for use in balancing the signals from the diodes. It was moved back and forth across the diode with two screws in the side of the mount. In addition to the weaker signal from the vertical component, imbalance also resulted from slight variations of the internal voltage sources. The diodes had very little noise, and test runs using a mercury light source showed that the signals could be balanced to within 20 microvolts. However, the sensitivity of the diodes was only .5 amps per watt, and because there was such a minute amount of scattered light, a signal of only a few hundred microvolts was expected. The

lens used by the diode to pick up the light signal is about the size of a pinhead, and required that the ray from the beam splitter be focused on it exactly. This adjustment was critical, and although the mounts holding the diodes were fairly easy to manipulate, alignment was difficult. This fact, coupled with the fact that the sensitivity was relatively low, was responsible for selection of RCA Victor 7102 photomultiplier tubes as detectors, in place of the photodiodes.

The photomultiplier tubes have two advantages over the photodiodes. The detecting surface is much larger so that alignment of the tube is not necessary. All that is required is to insure that the ray gets to the exit port in the side of the beam splitter. The tubes are permanently on the side ports and one tube is visible in Figure 2. Secondly, the sensitivity of the tubes is 400 amps per watt [Ref. 10], almost 1000 times as much as the photodiodes. The tubes used do not have as much response in the ruby wavelength region as did the photodiodes. However, the increase in sensitivity more than made up for this. A comparison between the diodes and photomultipliers was made, and the following results were obtained. Filters capable of reducing the intensity of ruby light by a factor of 10^{10} were placed in front of the monochromator. An aluminum rod was placed in the plasma chamber to simulate the plasma beam and the laser was fired. No signal was detected by the photodiodes, but a signal of a few millivolts was detected by the

photomultipliers. The laser was fired in the conventional mode during this test. After installation of the Pockels cell, measurements were taken again on the photomultipliers and a signal of five volts was obtained. It was concluded that the photomultipliers would be more suitable as detectors, although they required a 1000-volt power supply and they had a fairly high noise level. Initially, two power supplies were used to balance the tubes. However, it was found that balance could be better accomplished by placing a variable resistance in series with the tube having the highest signal, and adjusting the resistance to balance the signal. The tube with the lowest internal noise was placed in position to detect the laser signal.

Triggering of the oscilloscope was accomplished by using a PIN photodiode. A microscope slide was placed in a position either in front of or behind the laser, so that enough of the laser signal was reflected to give a signal from the diode. This signal can be displayed to monitor the pulse, or can be fed in to the external trigger terminal. In either position, it will serve as a trigger for the photomultiplier signal. When operating in the conventional mode, it was discovered that the flashlamp light rather than the laser light caused the scope to trigger if the gain was high and internal triggering was selected. This situation resulted when the laser signal to the diode was reduced by a factor of 10^3, with filters. It was eliminated by decreasing the gain and reducing the filtering. Use of the external

trigger also negated the flashlamp signal, since approximately .4 volts was required for external trigger operation and the flashlamp signal was only a few millivolts.

B. ALIGNMENT

Although the ability of the experimental equipment to function properly depended on several factors, one of the most significant, if not the most important, was accurate alignment. The pulsed laser produced a collimated beam with practically no dispersion, and if the beam is misdirected by even a small amount, the probability of detecting scattered light is greatly decreased. To insure that the maximum amount of scattered light reached the detectors, the following procedures were used.

The pulsed laser was aligned using the Korad optical collimator. This instrument contains its own light source and was mounted between the plasma chamber entrance port and the laser. The focusing lens had to be removed in order to mount the collimator, and the laser housing and head covering were removed so that the rod and front etalon could be adjusted. Prior to adjusting the laser, the ruby rod was checked to insure that the "C" plane was horizontal. The "C" plane can be determined by holding the rod in front of bright light and rotating it. In one direction the rod will appear darker, and this is the plane. The rod used in the laser had scratches on the ends, which identified the "C" plane. With the scratches in a horizontal plane, the "C"

plane was horizontal. It was noted that with the laser head on, the rod had a tendency to rotate so that the "C" plane shifted as much as 45°. In this position, the laser would not operate in a "Q"-switched mode, since "Q" switching requires that all components have the same polarization. Cause of this shift was probably motion due to vibration of the flashlamps at ignition. A noticeable decrease in output made this shift easily identifiable, and when lasing did not occur, this was one of the first things that was checked. With the room darkened, the collimator was turned on and positioned so that reflections from the front and rear reflectors and the rod were visible, when possible. The reflection from the front reflector is yellow and quite bright. The reflection from the ruby rod is a weak yellow spot, and the reflection from the rear mirror is red and very dim. The low intensity of the rear mirror reflection is due in part to the fact that the polarizer and Pockels cell are between the rod and mirror. If the reflection was not visible, the Pockels cell and Brewster stack were removed, and a rough alignment was made using the gas laser as a light source. The mirror was adjusted so that the alignment beam was perpendicular. This occurred when only one spot was visible on the back of the mirror. With all three reflections in the collimator, the rear mirror was adjusted so that its reflection was superimposed on the ruby rod reflection. Then the reflection from the front etalon was superimposed on the other two. It was necessary to align in that

order, because the front etalon reflection made the other two invisible. Although there are two adjusting screws for the ruby rod, it was not normally adjusted, since the front and back reflectors were much more easily and accurately positioned.

With the laser properly aligned, the next step was to position the Pockels cell and Brewster stack. First, the gas laser was adjusted so that its beam penetrated the center of the rod. Then, a vertical polarizer was placed at the rear of the Pockels cell and a horizontal polaroid was placed in front of the Brewster stack. With the gas laser beam directed through the polaroids, Pockels cell and Brewster stack, a Maltese cross shadow was formed and could be projected on a sheet of paper held in front of the forward polaroid. This cross was about the size of a quarter and fairly distinct. The Pockels cell was adjusted so that the center of the cross image was directly on the point where the laser beam hit the paper. Figure 4 illustrates the position of the polaroids and the image of the aligned cross.

Following the adjustment of the laser and Pockels cell, the gas laser was adjusted so that its beam coincided with the beam from the pulsed laser. This was accomplished by firing the pulsed laser entirely through the plasma chamber at an exposed, black polaroid print used as a target. (It was necessary to remove the light trap to have a clear path.) The film was mounted firmly on a cardboard attached to the platform holding the detectors, and the laser pulse

produced a burn pattern of about one-half inch diameter on it. The focusing lens also had to be removed, because, with it in place, the beam was dispersed so greatly by the time it reached the target that no burn pattern was visible. With the lens still removed, the gas laser was manipulated so that its beam struck the center of the burn pattern. In this position the beam was slightly above and to the right of the longitudinal axis of the ruby rod. The focusing lens was then replaced and adjusted so that the slightly dispersed beam from the gas laser was again centered on the burn pattern.

In order to transmit the beam to the monochromator, an aluminum rod with a polished beveled tip was inserted through the cathode until it intercepted the laser beam. The platform holding the laser was positioned so that the beam went straight through the entrance and opposite ports, and was adjusted in height until the beam hit the rod. The rod was in the same position as the plasma column and was rotated until a strong reflection was observed looking into the periscope. Then the periscope was adjusted so that the image of the beam struck the entrance slit of the monochromator. With the proper setting of the monochromator, the beam passed through the exit slit and calcite slab where it was divided into two components. Initial alignment was made by removing the cover of the monochromator and observing the path of the beam through the monochromator.

The calcite slab was positioned just outside of the monochromator exit slit, and the two components were easily observed by removing the cover of the beam splitter and inserting a piece of white paper as a screen. The beams were followed through the splitter, which was rotated until each beam was on a separate mirror and reflected to the exit port where the photomultiplier tube was mounted. It was essential that there be no mixing of the two beams, so adequate separation had to be insured. Figure 5 portrays the path of the rays from the monochromator to the photomultipliers.

Output from the photomultipliers was used to achieve the best alignment. It was necessary to place a chopper in the gas laser beam so that there would be an alternating signal that could be displayed. The chopper was normally mounted just forward of the pulsed laser. The monochromator and beam splitter were mounted on a single solid platform which pivoted from a point in the rear, and was moved by an adjusting bolt connected on the side. The periscope was connected to the monochromator by a channeled, light-weight piece of aluminum so that the laser beam would always strike the center of the monochromator focusing lens. The aluminum was held by a pin at the monochromator and was adjustable at the periscope. After a good signal was obtained by reflecting off the aluminum rod placed in the cathode (about .4 volts), it was replaced by an alumina rod with an extremely small diameter tip. This rod was rotated until a signal was

gained. The purpose of the alumina rod was to provide a more diffused reflected signal so as to better simulate the plasma and also to provide a more accurate focus on the center of the plasma.

Final adjustments with the alumina rod were made by first adjusting the monochromator for maximum signal on the oscilloscope. Then the periscope was adjusted and the platform holding the monochromator was positioned. Final adjustment was made by retuning the monochromator micrometer for maximum signal and then resetting it for ruby by subtracting 85 from the previously determined setting. A good signal from the alumina rod was about 15 millivolts.

The PIN diode used as a trigger was positioned visually in the gas laser beam. Occasionally, its output was also monitored to insure good alignment.

IV. EXPERIMENTAL PROCEDURES AND RESULTS

With the entire system aligned, preliminary tests were conducted to determine the voltage scale setting on the oscilloscope necessary to observe the scattered signal. Filters designed to reduce the intensity of ruby light were placed in front of the monochromator slit, so that the intensity was effectively reduced to 10^{-10} of the power output of the laser. The laser was fired and a signal of five volts was obtained.

As stated previously, the anticipated power loss was 10^{-14} to 10^{-15} when the laser pulse was reflected from the

plasma at a point near the cathode. The five-volt signal from the test firing indicated that the scattered pulse should give a signal between 100 and 1000 microvolts.

The Tektronix 7704 oscilloscope was operated using both a 7A22 fast rise amplifier and a 7A16 differential amplifier [Ref. 11]. The 7A22 amplifier had gain to 5 millivolts per centimeter, and the 7A16 had gain to 10 microvolts per centimeter. The 7A22 had the advantage of being better able to preserve the pulse shape of the scattered signal. This would be of great assistance in identifying the scattered signal with assurance. However, since it was not a differential amplifier, the plasma noise would obviously appear in the signal. Also, in order to accurately reproduce the pulse, a 50-ohm termination rather than a one-megohm was used, and this had the effect of reducing signal strength by 10^5. Since such a low signal was anticipated, use of the 7A22 was severely limited. Its use was attempted, however, and helium gas was used in the plasma chamber to reduce noise since it had no lines near the ruby wavelength. A cathode follower amplifier and pulse amplifier were added to the photomultiplier output to enable use of the 50-ohm termination without loss of signal strength. With this addition, it was possible to actually have the signal amplified 50 times its size leaving the photomultiplier. However, the noise from the photomultiplier was also increased by a factor of 50, and although this did not make detection impossible, it limited use of the amplifier (7A22) to about 20 volts

per centimeter. At this setting, no scattered signal was detected.

The 7A16 amplifier was operated using the output from both photomultipliers to cancel plasma noise. Since this amplifier had a slow rise time which would produce a distorted pulse, it was decided to use maximum possible gain, and sacrifice the integrity of the pulse shape. Therefore, the one-megohm termination and the 200 microvolt per centimeter scale were used. The one-megohm termination had the effect of flattening out the signal after it reached its peak value. This was confirmed by taking pictures of the trigger signal, which showed that on a 200 nanosecond per centimeter base, the signal sloped at about 45°, and then flattened completely at the peak value. The top photograph in Figure 6 is typical of the signals obtained. Although this type of signal would not be easy to identify if considerable noise were present, the high gain available made it the best prospect for success. Several runs were conducted using argon as the gas in the chamber and photographs of the signals from the photomultipliers showed a drop of about 200 microvolts. The pictures were not conclusive enough to state that the signal definitely was from the scattered light, however. Essentially, the procedure was to take several pictures with the plasma on, and then take several pictures with the plasma off. In general the pictures with the plasma off showed no slope. There were, however, some traces which were somewhat similar to those taken when the

plasma was on. Figure 6 shows the type of trace obtained. Further evidence tending to prove that the signal actually was scattered laser light was the fact that when the pressure of the argon gas, and thus the density, was increased, the signal appeared to be stronger. The possibility that the signals were caused by reflections from inside the plasma chamber was also considered. This was doubtful, however, since the signal did appear to depend on the gas pressure, while a reflected signal should have been constant with the plasma on or off. On one occasion a reflected signal was observed, but this situation was corrected by repositioning the light trap.

While attempting to improve the quality of the output signal, it was discovered that the Pockels cell emitted strong electromagnetic radiation signals when it was pulsed at the time of the laser firing. These undesired signals were detected and transmitted to the oscilloscope by the photomultiplier cables, photodiode cable, and in one instance, by an unconnected cable which happened to be near the Pockels cell and extended to within three feet of the scope. Although the signal was not always detected, it normally appeared and was superimposed on the photomultiplier signal. The magnitude was as much as .1 volts, and since measurements were being taken on the 200 microvolt setting, the radiation had to be eliminated. First efforts involved double-shielding the photodiode cable, checking the integrity of the photomultiplier cables (which were already double-

shielded), positioning the photodiode as far as possible from the Pockels cell, and shielding the Pockels cell with aluminum foil. This initially appeared to be an adequate solution. The fluctuations of the trace on the picture in Figure 6, taken after the previously mentioned corrections were completed, were attributed to noise from the Pockels cell. Although this noise distorted the trace considerably, it did not make it unusable.

Unexplainably, during the next attempt to obtain data, the noise again became intolerable. The solution this time was to move the oscilloscope and trigger diode into a screen room. Shielded cables were again used to connect the photomultipliers to the scope. Since the screen room was designed to keep out all stray radiation, it was anticipated that the signal would be purely from the laser and plasma. However, first observations in the screen room indicated that, if anything, the undesired signal was stronger. The probable explanation was that the cables were picking up the signal through the metal frame which supported them. The cables also passed almost directly over the Pockels cell and the ground for the plasma machine, cable support and Pockels cell was common. It is almost certain that these factors were at least in part responsible. Another likely source of pickup of the noise was the cable connection to the photomultipliers. These were originally threaded connectors, but had to be changed to bayonet type for use with the screen room cables.

Final attempts to achieve detection of the scattered signal were made after a cover was constructed for the Pockels cell in an effort to provide an adequate electromagnetic shield. This endeavor significantly reduced fluctuations such as those appearing in Figure 6 but, when the laser was fired with the plasma beam off, a signal closely resembling the laser pulse was obtained. The signal varied in magnitude from 25 to 125 millivolts and, since it was detected with all light blocked from the photomultiplier, the possibility of internal reflections was eliminated. Although the source of the signal could not be positively identified, it appeared to be related to the pulse applied to the Pockels cell. Efforts made to eliminate the signal were unsuccessful.

Although the signal from the scattered light could not be positively identified, it apparently was present when observations such as those in Figure 6 were made. This detection was made possible by an improved alignment and focusing system, a light trap, and a "Q"-switched laser pulse. The development of these systems was the most important result of this experiment.

V. RECOMMENDATIONS

The most difficult problem left to solve before a scattered laser light signal can be detected accurately is elimination of unwanted electromagnetic signals. Various attempts to reduce the noise were made but this objective was not accomplished. The problem is severe and must not be underestimated. However, a methodical, step-by-step approach should produce isolation of the signal source and thus lead to the elimination of the path which conducts the unwanted signal.

In order to achieve greater signal strength at the detector, the possibility of utilizing an interference filter in conjunction with a photomultiplier tube is suggested. A filter designed to allow transmission of ruby light only could be mounted over the top port with a photomultiplier tube directly above it. This would eliminate the need for the monochromater and beam splitter and would reduce the accuracy required for alignment. This method would also allow more flexibility in movement of the system to different positions in the chamber.

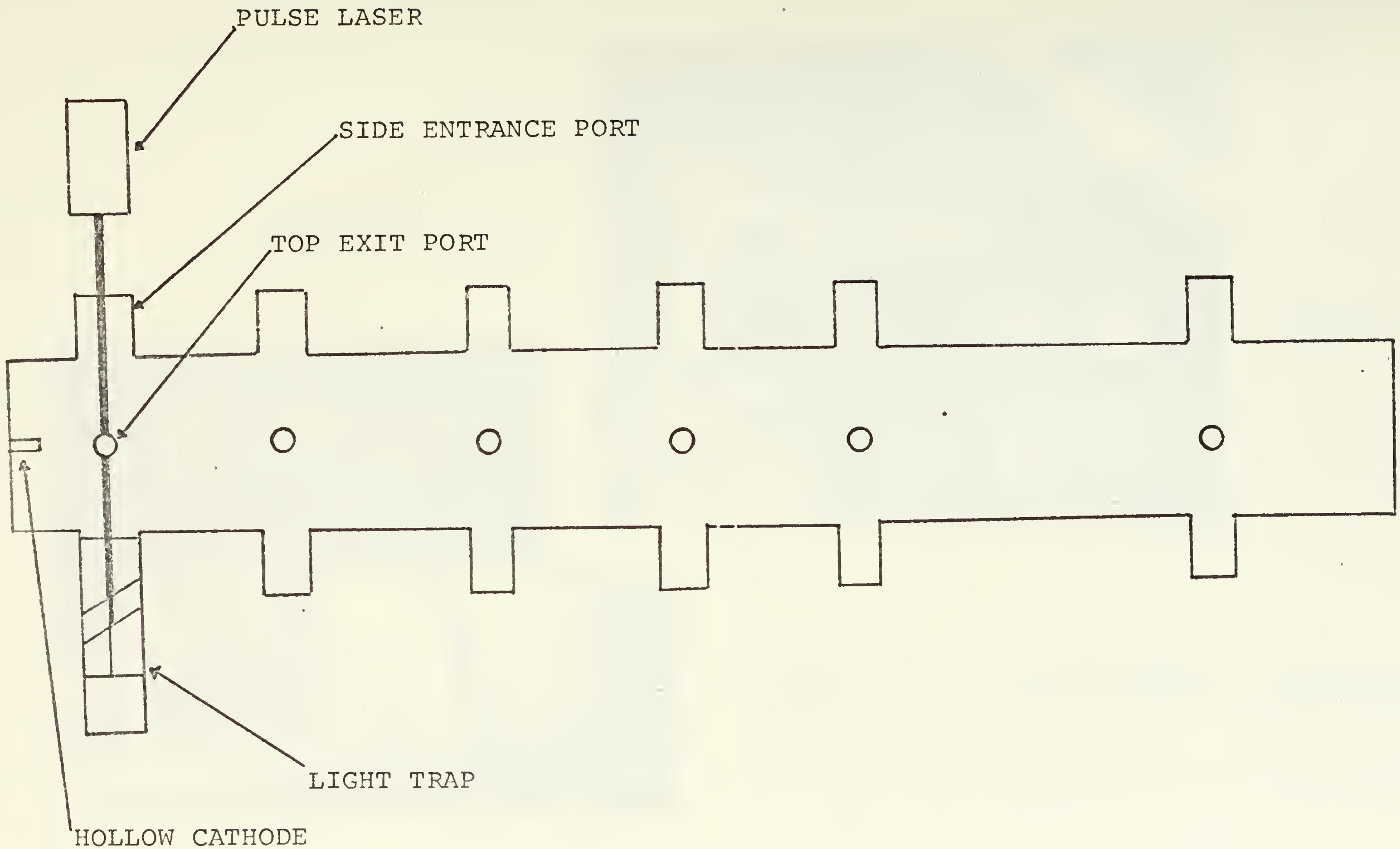

PULSE LASER
SIDE ENTRANCE PORT
TOP EXIT PORT
LIGHT TRAP
HOLLOW CATHODE

Figure 1

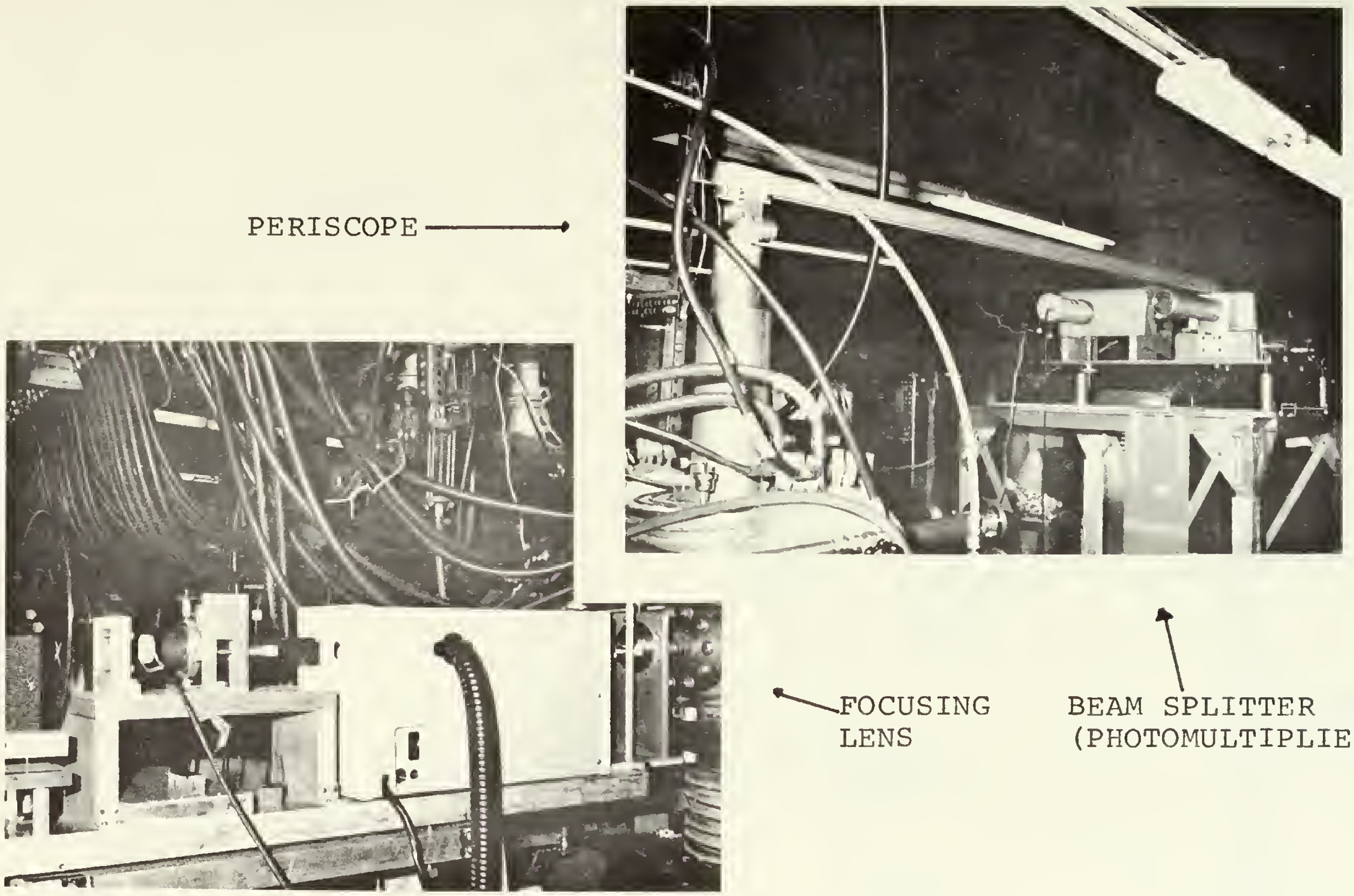

PERISCOPE
MONOCHROMATOR
FOCUSING
LENS
BEAM SPLITTER
(PHOTOMULTIPLIER EXTENDING)
REAR
REFLECTOR
POCKELS
CELL
BREWSTER
STACK
PULSE LASER

Figure 2

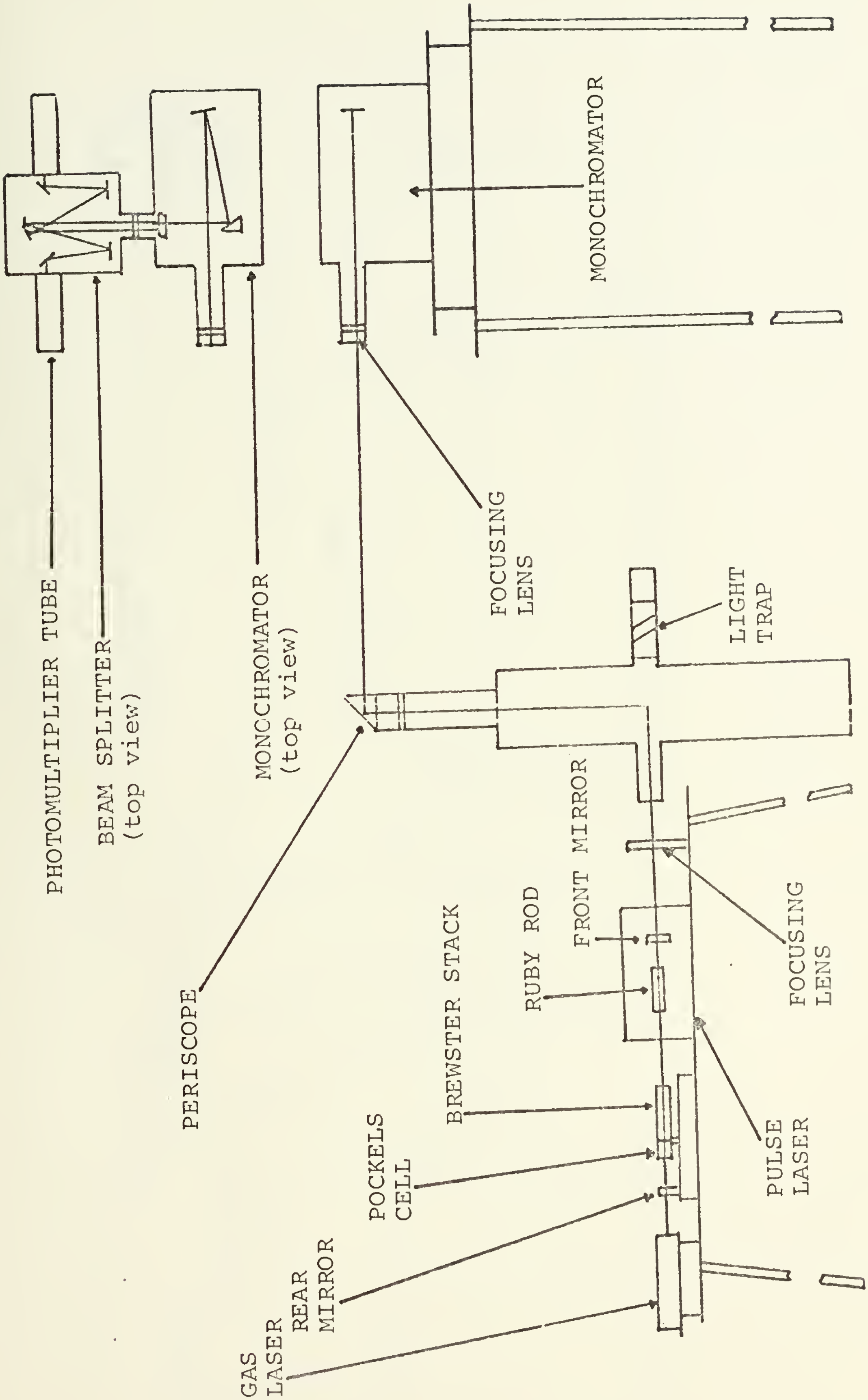
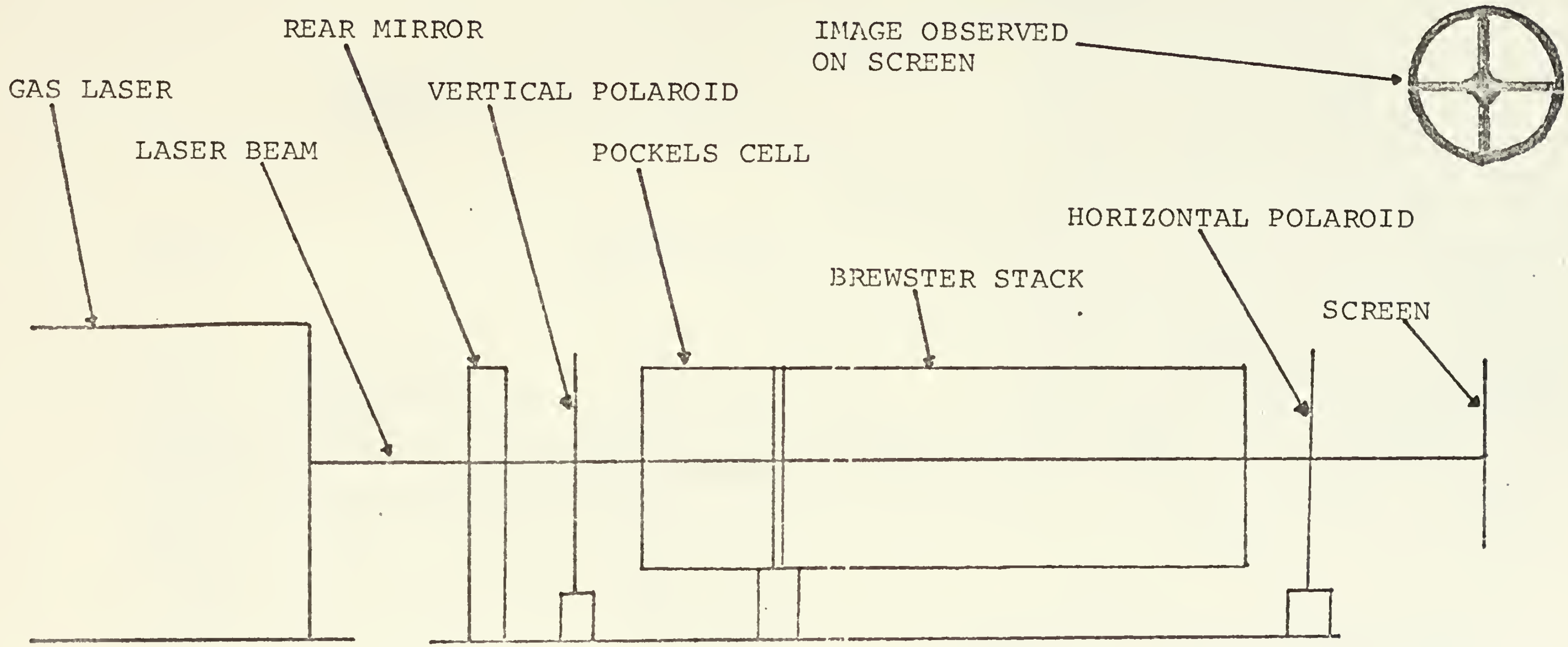
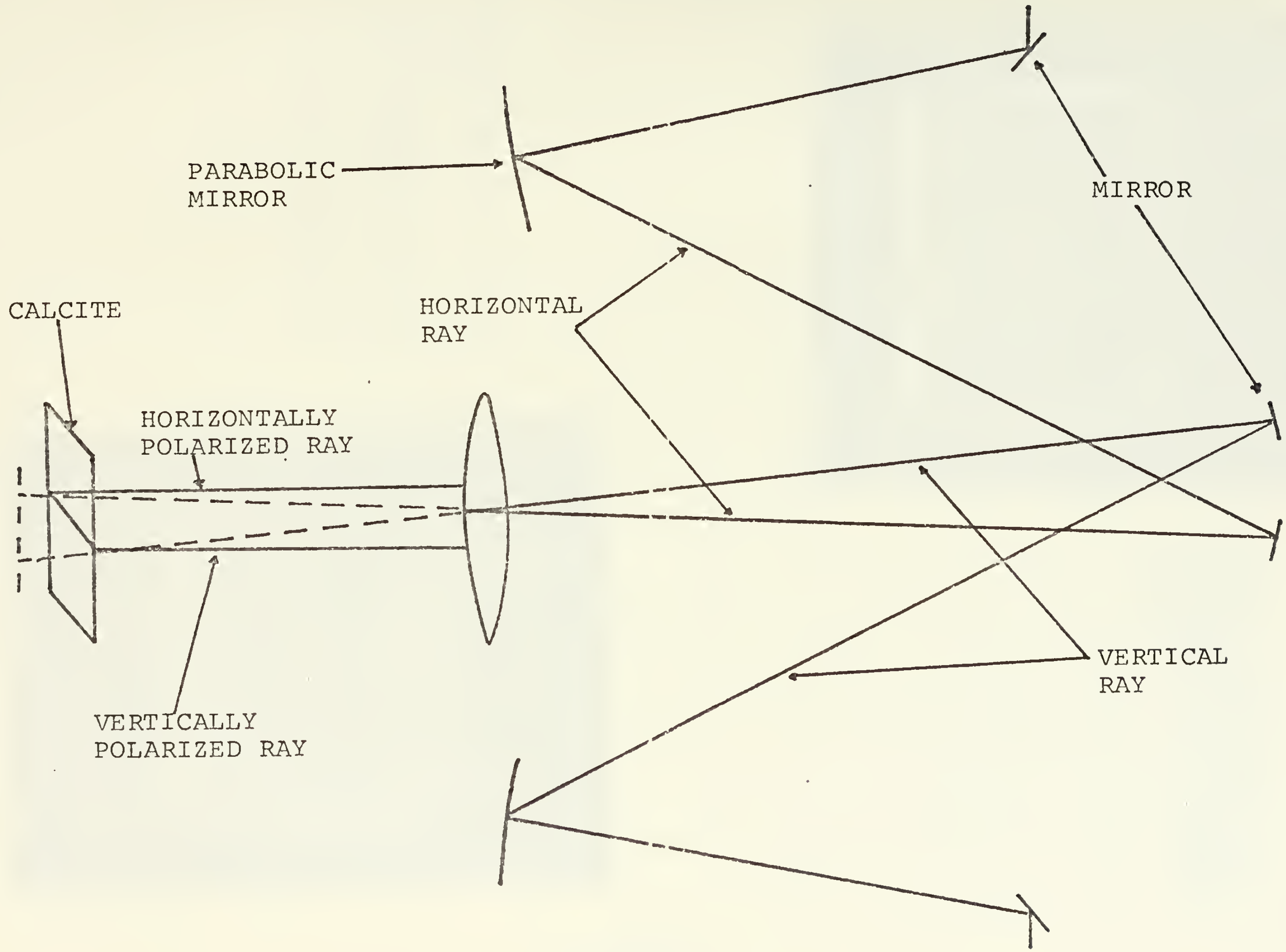

PHOTOMULTIPLIER TUBE
BEAM SPLITTER
(top view)
MONOCHROMATOR
(top view)
MONOCHROMATOR
FOCUSING
LENS
LIGHT
TRAP
PERISCOPE
FRONT MIRROR
RUBY ROD
BREWSTER STACK
FOCUSING
LENS
POCKELS
CELL
PULSE
LASER
REAR
MIRROR
GAS
LASER

Figure 3



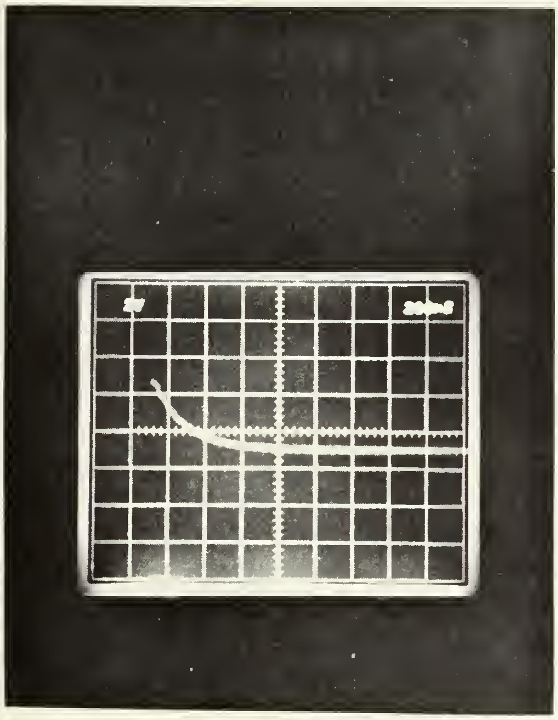
GAS LASER
LASER BEAM
REAR MIRROR
VERTICAL POLAROID
POCKELS CELL
IMAGE OBSERVED ON SCREEN
BREWSTER STACK
HORIZONTAL POLAROID
SCREEN

Figure 4



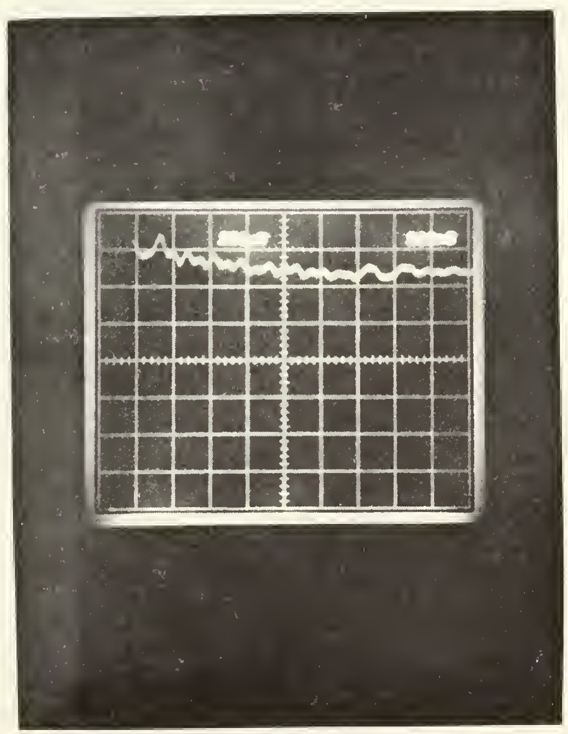
PARABOLIC
MIRROR
MIRROR
CALCITE
HORIZONTAL
RAY
HORIZONTALLY
POLARIZED RAY
VERTICALLY
POLARIZED RAY
VERTICAL
RAY

Figure 5



Signal scattered from aluminum rod (1 megohm termination at oscilloscope)

Figure 6



Suspected signal from plasma

Fluctuations caused by noise from Pockels cell

(1 megohm termination)

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13. ABSTRACT

Measurement of plasma density and temperature was attempted using the technique of scattering laser light from the plasma and comparing the magnitudes of the scattered and input intensities. Although no significant results were obtained, a scattered signal was apparently obtained using a giant pulse laser. Both PIN photodiodes and photomultiplier tubes were used as detectors, and comparison showed the photomultipliers were more suitable. The most important results were modification of the laser to operate with a Pockels cell in a "Q"-switched mode, improvement of the optical alignment system, and use of a light trap to eliminate internal reflected signals.

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